THE OXYGEN ISOTOPE COMPOSITION OF DARK INCLUSIONS IN HEDs, ORDINARY AND CARBONACEOUS CHONDRITES. R. C. Greenwood[1], M. E. Zolensky[2], P.C. Buchanan[3], I.A. Franchi[1]. [1]Planetary and Space Sciences, The Open University, Milton Keynes MK7 6AA, UK (r.c.greenwood@open.ac.uk). [2]ARES, Johnson Space Center, Houston TX, USA.[3]Kilgore College, Kilgore, Texas 75662 USA.

Introduction: Dark inclusions (DIs) are lithic fragments that form a volumetrically small, but important, component in carbonaceous chondrites [1,2]. Carbonaceous clasts similar to DIs are also found in some ordinary chondrites and HEDs [3,4]. DIs are of particular interest because they provide a record of nebular and planetary processes distinct from that of their host meteorite [1,5]. DIs may be representative of the material that delivered water and other volatiles to early Earth as a late veneer [6]. Here we focus on the oxygen isotopic composition of DIs in a variety of settings with the aim of understanding their formational history and relationship to the enclosing host meteorite.

Materials and methods: DIs and related materials were obtained from the following meteorites: *CV3s (Allende, NWA 2140, NWA 2364):* Samples from Allende cover all categories of the four-fold classification scheme [2] (inclusion numbers analyzed in brackets). Type A clasts (*1a1*, *4b1*, *25s1-TW1*) contain chondrules, inclusions and matrix, but are somewhat finer grained than normal Allende material. Type A/B clasts (*MZB*) are transitional between Types A and B (Fig. 1). Type B clasts (*12b1*) contain opaque matrix and olivine-rich aggregates and may have experienced a hydration-dehydration cycle [2]. Type C clasts (*5a1*, *ekpb4b1*, *MZ15*, *USNM 3876*) consist of fine-grained, opaque material similar to Allende matrix. Full descriptions for of the Allende DI samples are given in [2]. DI material from NWA 2140 analyzed for this study is Type A/B and Type A for NWA 2364. *HEDs: (Bholghati, PRA 04401, SCO 06040).* DIs from the howardite Bholghati have not been analyzed by us for oxygen isotopes. Instead a sequence of 5-10 mg representative whole rock samples have been run to assess its carbonaceous chondrite content. PRA 04401 is an extremely coarse-grained howardite containing a high concentration (~40-50% in places) of nearly cm-sized angular carbonaceous clasts that texturally resemble CM2 material [7]. SCO 06040 is also a coarse-grained howardite breccia, contains a lower amount (~10%) of rounded, up to 2mm diameter, CM2-like clasts [7]. *OCs: Sharps (H3.4)* is a fragmental breccia containing accessory carbonaceous clasts up to 1 cm in diameter [8].

Oxygen isotope analysis was performed by infrared laser-assisted fluorination [9]. All analyses were obtained on untreated whole rock samples (0.5-2 mg). System precision, as determined on an internal obsidian standard is: ±0.05‰ for $\delta^{17}O$; ±0.09‰ for $\delta^{18}O$; ±0.02‰ for $\Delta^{17}O$ (2σ).

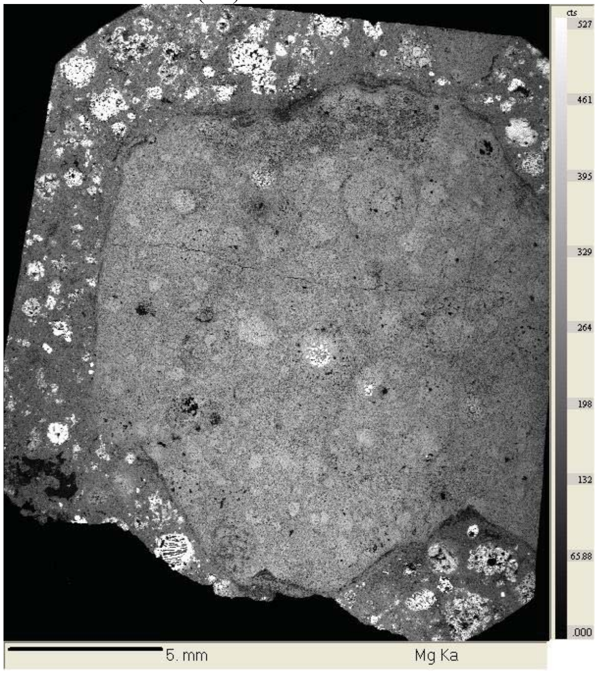

Fig. 1 Mg Map of a Type A/B Allende clast (AMNH 4301 [1]). Remnants of primary material are present in the centre of some larger chondrules.

Results: All of the Allende DIs are displaced slightly to the right of the CCAM line in Fig.2 and define a linear trend with a slope of y = -4.30 + 0.89x R^2 = 0.99. The less altered chondrule-bearing clasts (A and A/B) plot closest to bulk Allende analysis in Fig. 2, with the most altered clast (Type B) (*12b1*) being approximately 5‰ heavier with respect to $\delta^{18}O$. Matrix-rich Type C clasts show a narrow range of oxygen isotope variation, plotting roughly halfway between the most and least altered DIs in Fig. 2. These results are in agreement with previous studies of Allende DIs [1].

DIs in CV3s NWA 2140 and NWA 2364 (Type A/B and A respectively) plot at the higher $\delta^{18}O$ values than their equivalents in Allende (Fig. 2). This is consistent with the results of previous studies [1] which found that Allende DIs are relatively ^{16}O-enriched compared to inclusions in other CV3s (Fig.3).

Carbonaceous chondrite clast material from the howardite PRA 04401 plots at the extension of the CM2 field in Fig. 2 consistent with results of textural and mineralogical studies [7]. The other howardite samples analyzed in this study (SCO 06040 and Bholghati) have $\Delta^{17}O$ values that vary from -0.265 to -0.489‰, consistent with bulk carbonaceous chondrite (CM2) contents of between about 1 and 10%.

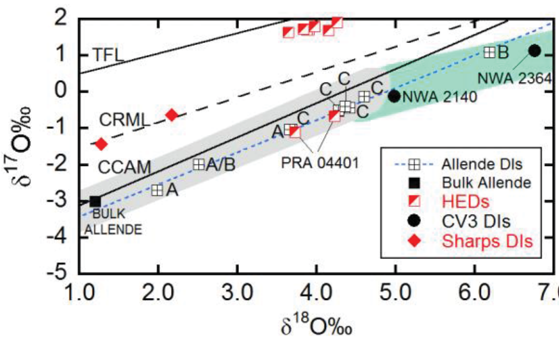

Fig. 2 Oxygen isotopic composition of Dark Inclusions. The blue dashed line is the best fit line through the Allende DIs only. Bulk Allende [10]. TFL = Terrestrial Fractionation Line, CRML = CR Mixing Line [11], CCAM = Carbonaceous Chondrite Anhydrous Mineral line [12]. CM2 field (blue shading) [12], CV-CK field (grey shading) [10].

DIs analyzed in Sharps are clearly distinct from those in either the CV3s or howardites and plot on the CR Mixing Line [11]. The composition of these DIs is not well understood, although they do not appear to be mineralogically related to CR chondrites [8].

Discussion: Mineralogical studies of DIs have played a crucial role in highlighting the importance of parent body processes in modifying the composition of CV chondrites [2, 13]. In particular, DI studies have shown that CV3s, previously regarded as pristine nebular condensates, underwent extensive aqueous alteration [2, 13]. Furthermore, textural evidence indicates that, following aqueous alteration, some DIs experienced a phase of thermal metamorphism, resulting in phyllosilicate dehydration and the formation of secondary Fe-rich olivine (Type B inclusions) [13]. This model was later extended to explain the origin of CV3 Fe-rich matrix olivines in general [14].

The results of previous oxygen isotope studies of DIs have also pointed to the role of aqueous alteration in modifying their primary compositions [1]. As shown in this study, DIs define linear arrays with a shallower slope than the CCAM and with less altered material plotting at the ^{16}O-rich end (Type As) and more altered material (Type Bs) at the ^{16}O-poor end [1]. However, with respect to phyllosilicate dehydration and secondary Fe-rich olivine formation, oxygen isotope evidence appears less clear-cut [15]. Experimental evidence indicates that dehydration will result in heavy-isotope enrichments, which for Allende matrix olivines are not seen, if the CCAM line is used as a reference [15].

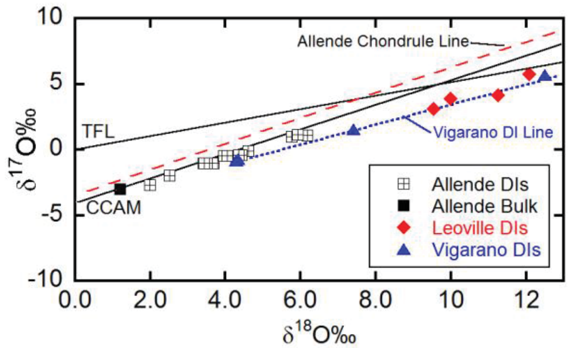

Fig. 3 Oxygen isotope composition of DIs in CV3 chondrites. Data this study and [1] (see text for details).

However, DIs in Allende may point to a possible weakness in this argument. In Fig. 2 and 3 DIs do not sit on the CCAM line, but instead define a line of lower slope (Fig. 2). In a similar way, chondrules in Allende plot on a discrete line with a steeper slope than the CCAM line. Analysis of 22 Allende chondrules (OU unpublished data) yield an array with a slope of: y = -3.45 + 0.97x (Fig. 3). If this reference line, rather than the CCAM, is used positive shifts of 7‰ along a mass fractionation line to the array defined by Vigarano DIs is feasible (Fig. 3). This is greater than required by earlier experiments [15]. More recent work has shown that shifts of 7‰ are produced during dehydration of serpentine [16]. Thus, phyllosilicate dehydration, leading to the formation of CV3 Fe-rich matrix olivines, may be a viable mechanism, provided the relevant reference line is steeper than the CCAM [17].

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